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Procedia Engineering 29 (2012) 2257 – 2264

Procedia Engineering

www.elsevier.com/locate/procedia

2012 International Workshop on Information and Electronics Engineering (IWIEE)

A Fast Carrier Synchronization Method for Earth-Space Communication Systems

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Abstract

This paper presents a fast carrier synchronization method for earth-space communication systems in which pseudnoise (PN) sequence is adopted to help carrier synchronization. The method utilizes PN parallel correlation since it can provide a wide acquisition range while reducing the acquisition time. Moreover, a fine PN tracking is introduced to ensure the robustness of the proposed method. Simulations in MATLAB show that the proposed method can provide wide acquisition range, short acquisition time and small tracking jitter in both distorted static and dynamic channels.

Keywords: earth-space communication; carrier synchronization; PN acquisition; parallel- correlation; phase-locked-loop

1. Introduction

The carrier frequency offset greatly impairs the performance of a communication system. When using coherent demodulation, the receiver should estimate an accurate frequency offset from the received signals. A lot of researches have been done over the years to recover carrier frequency in single-carrier or multi-carrier systems. ATSC uses pilot signals to estimate the carrier frequency offset [1]. DVB-T adopts data direct carrier synchronization method [2]. Tsinghua University presents an algorithm that multiplies the delayed received signals to estimate the carrier frequency offset for the TDS-OFDM system.

This paper focuses on the fast carrier synchronization for earth-space communication systems. Different from ground communications, earth-space communication has more complex channel

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doi:10.1016/j.proeng.2012.01.298

environment due to the long distance and the relative motion between spacecrafts and ground stations. Thus earth-space communication systems require a faster and more effective carrier synchronization method. As the rapid development of international space technology, further researches on carrier synchronization based on existing method have great value.

2. Prior carrier synchronization approaches

There are two most commonly used approaches to recover carrier: one is the external synchronization which sends a weak carrier signal accompanying the transmitted signals. The carrier signal is called pilot. The other is the self-synchronization which directly extracts carrier from the modulated signals such as PN acquisition.

2.1. Pilot acquisition

ATSC is just an example which uses pilot to help recover carrier. Firstly, a narrow-band filter at the receiving end is used to filter out the pilot signal from received signals. Then the receiver uses a frequency-locked phase-locked loop (FPLL) to perform carrier acquisition, the offset is estimated by comparing the frequency and phase of the pilot signal with the local voltage-controlled oscillator (VCO).

This approach recovers carrier entirely based on pilot. However, inserting pilot will not only increase the transmission power, but also may cause interference with adjacent channels. Moreover, when there are strong multi path interferences, the pilot signal could be significantly attenuated by spectrum nulls. When there are heavy noise interferences, or a poor signal to noise ratio, this approach may be useless.

2.2. PN acquisition

It is required to insert known PN sequences in transmitted signals when using PN acquisition to recover carrier. The PN sequences are usually inserted at the head of every data frame.

Assume the frequency offset is Δf , the received data can be represented as

$$r_K = a_k e^{j2\pi\Delta f k T_S} + n_k \tag{1}$$

Where a_k is the transmitted symbol, T_S denotes the time duration of each symbol and n_k is the Gaussian white noise.

Local PN sequence generator provides the same PN sequences as that inserted in transmitted signals. Correlate the received data with the locally generated PN sequences, the correlation value of two consecutive *M* symbols (*M≤2/N*) in one PN sequence can be represented as (2) and (3).

$$corr(n)_{before} = \sum_{i=0}^{M-1} a(n-i) e^{j2\pi\Delta f(n-i)T_S} p(i) \tag{2}$$

$$\begin{aligned} corr(n)_{after} &= \sum_{i=M}^{2M-1} a(n-i) e^{j2\pi\Delta f(n-i)T_S} p(i) = \sum_{i=0}^{M-1} a(n+M-i) e^{j2\pi\Delta f(n+M-i)T_S} p(i) \\ &= corr(n)_{before} e^{j2\pi\Delta f M T_S} \end{aligned} \tag{3}$$

One can derive the phase offset of the two correlation values

$$\Delta\varphi = 2\pi\Delta f M T_S \pm 2k\pi, k \in Z \tag{4}$$

Then the estimated frequency offset is obtained

$$\Delta f = \Delta\varphi / (2\pi M T_S) \tag{5}$$

The frequency offset range that can be detected is

$$-\frac{1}{2MT_S} < \Delta f < \frac{1}{2MT_S} \tag{6}$$

From (6), one can find that if M decreases, the acquisition range will increase. However, there will be some loss of correlation gain, which may increase the tracking jitter.

3. The proposed fast carrier synchronization scheme

This paper proposed a fast carrier synchronization scheme based on PN acquisition. The scheme includes three different states and a state controller. The three states are parallel correlation peak acquisition, coarse PN acquisition and fine PN tracking. The block diagram is shown in Fig.1. The state controller is an important part that switches the current state automatically via estimating the remaining frequency offset.

3.1. Parallel correlation peak acquisition

The frequency offset will beyond the detection range of PN acquisition when the channel environment is very bad. If directly go to the PN acquisition state, the system would not work. In order to determine the frame header location, frequency-sweep acquisition is usually used to find a base frequency point near the optimum one [3]. However, since frequency-sweep needs repeat searching procedure on each point until finding the right one, it costs a lot of time.

In order to reduce the acquisition time, the carrier synchronization method proposed in this paper does not use frequency-sweep. Meanwhile, a parallel correlation algorithm is adopted in order to maintain a relatively wide acquisition range. The algorithm uses N PN sequence generators that can generate N partial PN sequences and each partial sequence is part of the original PN sequence. The received data is correlated with the N partial PN sequences respectively, and then send the N outputs into a comb filter which has a number of absolute value calculation units, delay units and adder units. The filter can calculate the sum of the N correlation values and export the total normalized correlation value. The normalized correlation value goes into a peak detection unit to find out the peak value. If the peak value is lager than a predefined threshold in several consecutive frames, a frame header indicator signal is given and the system goes to PN acquisition state.

According to the analysis in section 2.2, it is preferred to have shorter partial sequences because the shorter the interval length M of two correlations is, the wider the acquisition range can achieve. However, it is also preferred to have longer partial sequences so that there will be more correlation gain for noise

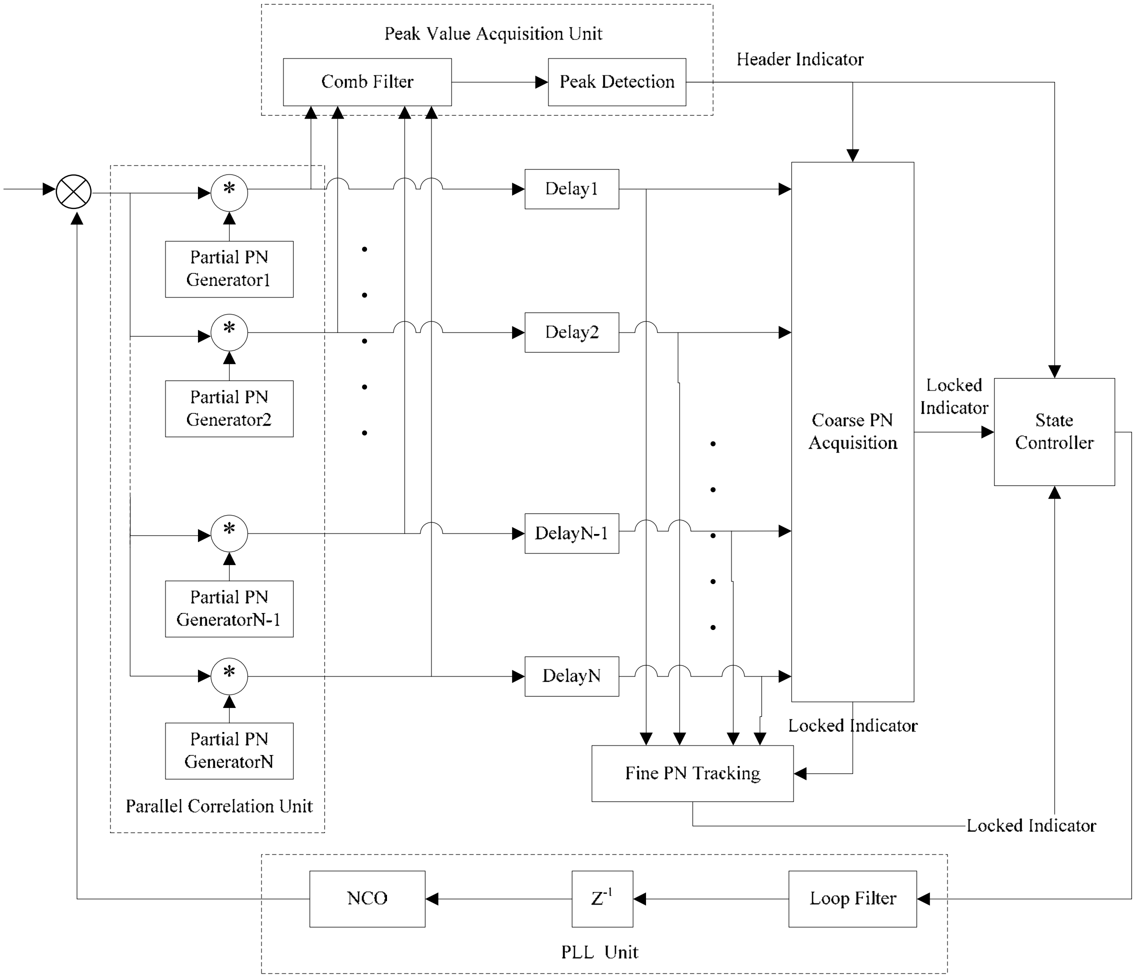

Fig.1 Block diagram of the proposed carrier synchronization scheme.

and multi paths rejection. So there is a tradeoff between the interval length and the number of accumulated symbols.

In ref.[4], a number of ways to generate partial PN sequences were presented. It can make the partial sequences overlap each other to generate more partial sequences. The interval length between two correlations is shorter, so a wider acquisition range is obtained. Moreover, the relation of each partial sequence also becomes stronger so that the system have a better noise rejecting performance.

3.2. Coarse PN Acquisition

After the parallel correlation peak acquisition state, the remaining frequency offset is relatively small. Then the system goes to PN acquisition to further reduce the jitter.

In the coarse PN acquisition state, the carrier offset is calculated in one frame. Because the correlation values of the *N* partial sequences have already been calculated, the average of *N-1* phase angle differences can be used, improving the estimate accuracy, as shown in Fig.2. The carrier frequency offset is

$$\Delta f = \frac{(\arg 2 - \arg 1) + (\arg 3 - \arg 2) + \cdots (\arg N - \arg(N-1))}{2\pi M\,(N-1)T_S} \quad (7)$$

3.3. Fine PN tracking

In this state, the remaining frequency offset is so small that the phase offset in M symbols' duration can not be easily detected. Thus, we need to expand the observation window of correlation between the received data and the local PN sequence in frames.

Assume that the correlation peak value of one frame can be represented as

$$corr\_f1 = E_S \sum_{i=0}^{N-1} e^{j2\pi\Delta f i T_S} \quad (8)$$

The correlation peak for the next frame is

$$corr\_f2 = E_S e^{j2\pi\Delta f L T_S} \sum_{i=0}^{N-1} e^{j2\pi\Delta f i T_S} \quad (9)$$

Then the estimated frequency offset can be expressed as

$$\Delta f = \frac{\arg(corr\_f2) - \arg(corr\_f1)}{2\pi L T_S} \quad (10)$$

Since the correlation gain is at least 3dB higher than that in the coarse PN acquisition, the tracking jitter is reduced. If extend the window to N frames, the resolution would be much higher.

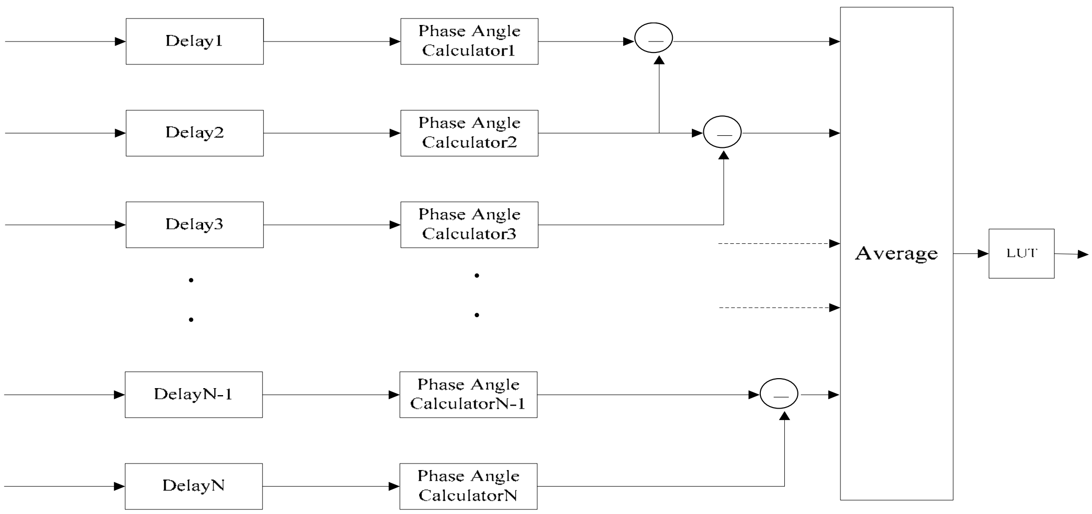

Fig.2 Block diagram of the coarse PN acquisition.

4. Simulation results

Simulations are carried out using MATLAB. The frame header is chosen as PN256, data rate is 9MHz . Every partial PN sequence has a length 32 with no overlap. So the acquisition range is

$$(-\frac{1}{2M},\frac{1}{2M}]\cdot \mathrm{B}=(-\frac{1}{2*32},\frac{1}{2*32}]\cdot 9M\mathrm{Hz}\text{=(-140.625KHz,140.625KHz]} \qquad (11)$$

Two typical channel models are simulated, including high-elevation channel and low-elevation channel. In order to test the carrier synchronization performance, the frequency-sweep synchronization is taken as the reference scheme.

4.1. High-elevation channel

Set the conditions of simulation as follows:

- Modulation: QPSK; Transmission bandwidth: 9MHz
- Fixed carrier frequency offset: 100KHz
- Phase jitter: 0
- Signal to Noise Ratio (SNR): 10dB

The estimated frequency offset values and errors of both two schemes are shown as Fig.3 and 4, respectively.

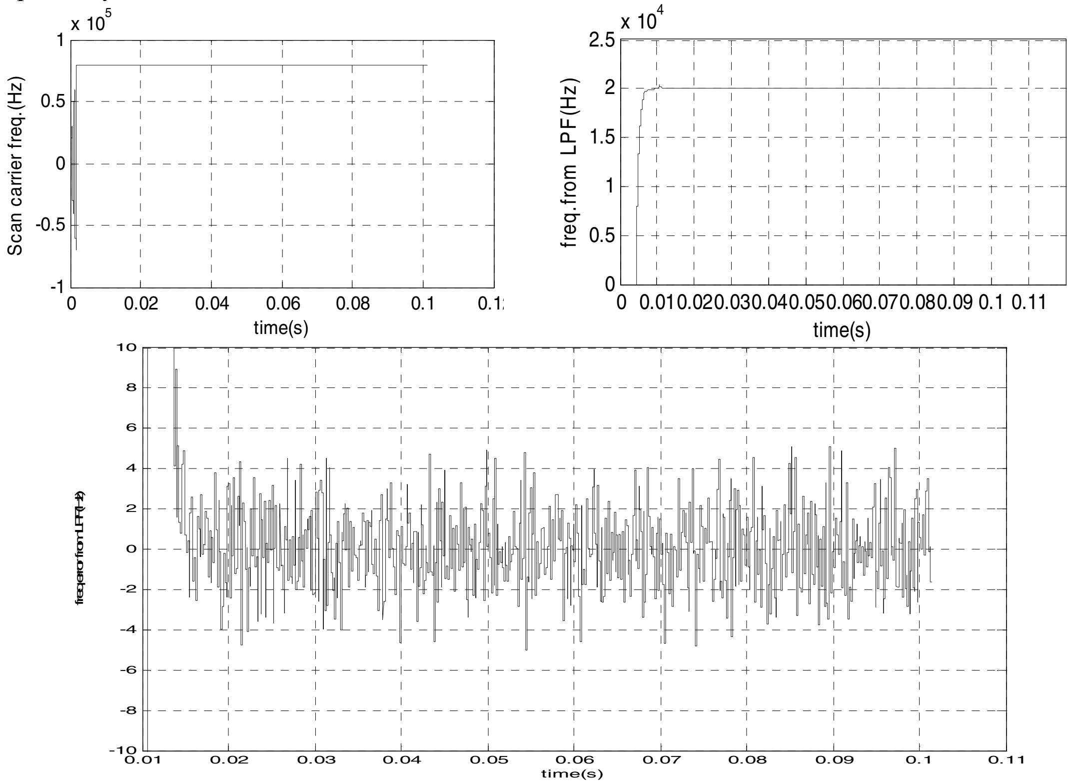

Fig.3 (a) (b) estimated frequency offset of frequency-sweep scheme; (c) estimate error of frequency-sweep scheme (high-elevation)

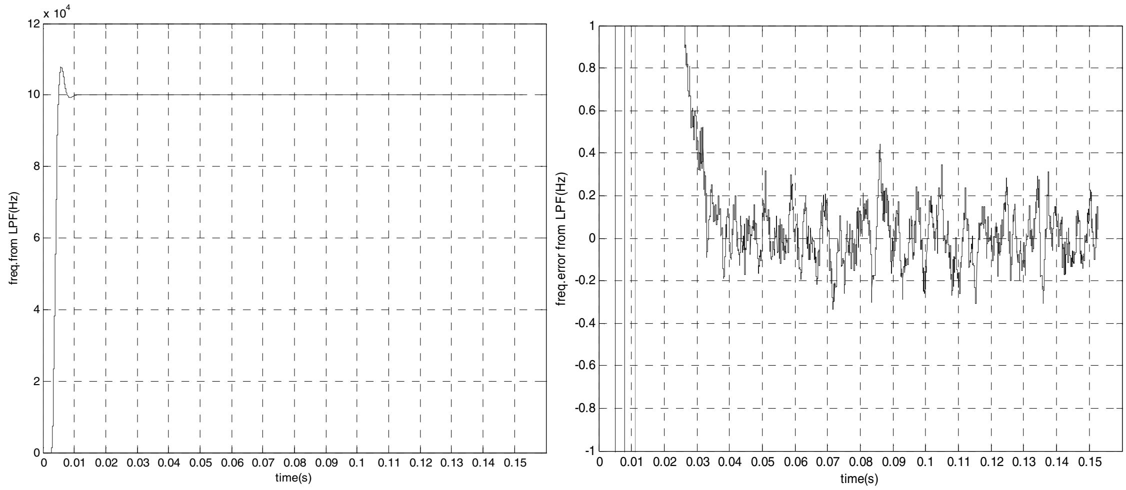

Fig.4 (a) estimated frequency offset of proposed scheme; (b) estimate error of proposed scheme (high-elevation)

4.2. Low- elevation channel

- Modulation: QPSK; Transmission bandwidth: 9MHz
- Fixed carrier frequency offset: 1000Hz
- Relative frequency offset: straight doppler shift 100Hz, doppler expand 100Hz, straight gain100
- Phase jitter: 0
- Signal to Noise Ratio (SNR): 10dB

  The estimated frequency offset and errors of both two schemes are shown as Fig.5 and 6, respectively.

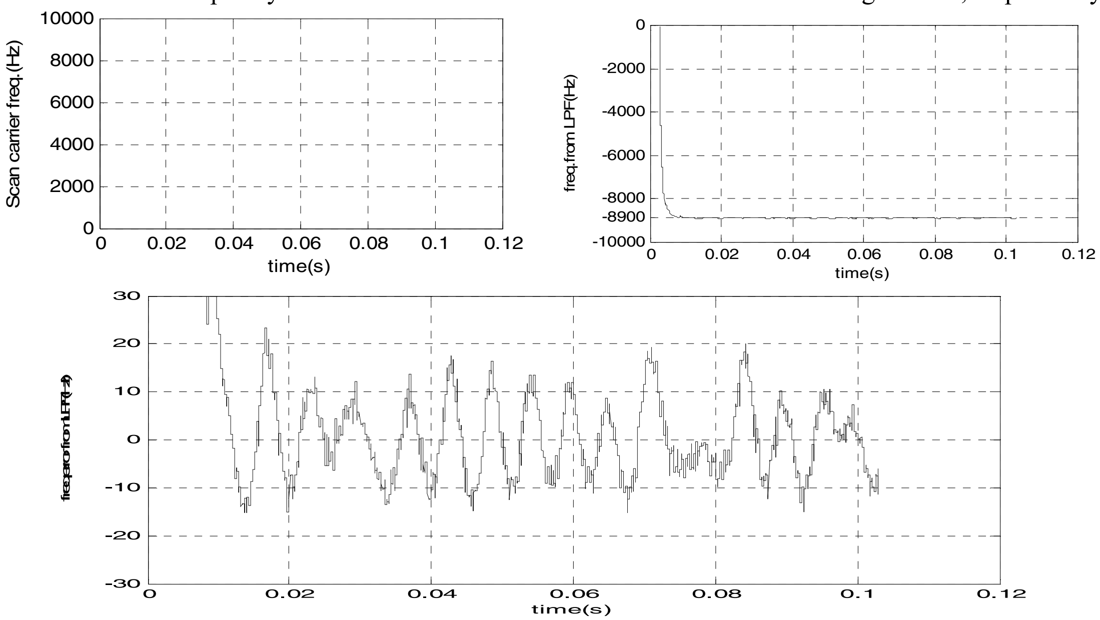

Fig.5 (a) (b) estimated frequency offset of frequency-sweep scheme; (c) estimate error of frequency-sweep scheme (low-elevation)

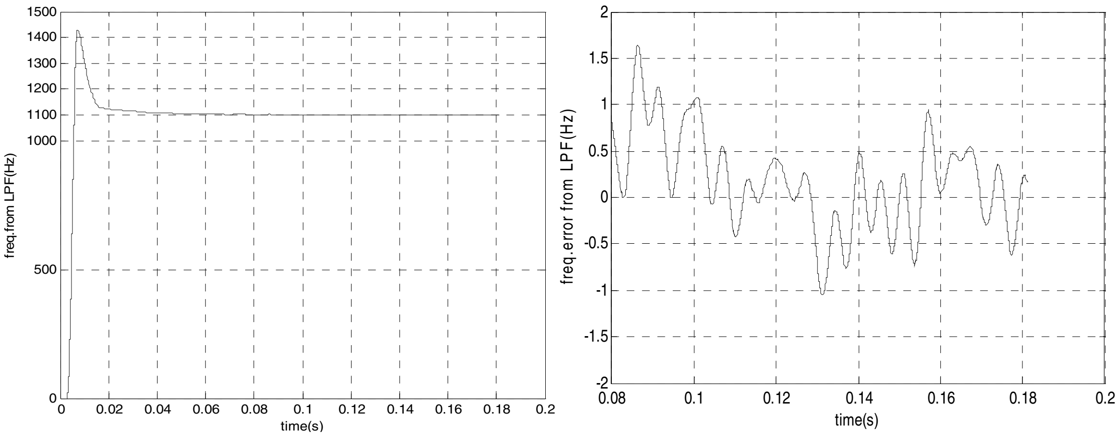

Fig.6 (a) estimated frequency offset of proposed scheme; (b) estimate error of proposed scheme (low-elevation)

From Fig.3 and 4, one can find that, in the high-elevation channel, the convergence time of the reference scheme is about 0.01s and the tracking jitter is ±5Hz, while using the proposed scheme, it has already converged within ±5Hz before 0.01s and the tracking jitter is ±0.4Hz which is much smaller than the reference scheme.

In order to design the scheme more suitable for dynamic channel, further improvement is carried out to the parameters of the PLL [5]. In the implementation, the controller is used to adjust the coefficients of the loop filter adaptively. When the carrier frequency offset is large, larger coefficients are selected so that the system can achieve a fast convergence speed. But it also increases the loop bandwidth, resulting in the increase of noise power. When the estimated frequency offset is small, smaller coefficients are selected in order to get small tracking jitter, but the convergence time increases correspondingly. It can be found from Fig.5 and 6 that, the convergence time of the improved scheme becomes a bit slow but the tracking jitter is much smaller than the reference scheme.

5. Conclusion

This paper presents a fast carrier synchronization method for earth-space communication systems, including parallel correlation peak acquisition, coarse PN acquisition, fine PN tracking and a state controller. Simulations show that the proposed method has wide acquisition range and dramatically reduces acquisition time and tracking jitter. It is more suitable for earth-space communication systems.

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